Aerospace Battery Development for the Exploration System Technology Development Program

Tom Miller
RPC/Electrochemistry Branch

August 4, 2006
NASA Glenn Research Center
Cleveland, OH

Energy Storage Project Background

- Exploration Systems Technology Development Program Objectives
  - Mature advanced technologies to TRL 6
  - Integrate component technologies into prototype systems to validate performance
  - Transition technology products to Project Constellation
  - Mature key technologies to support various missions
    - Crew Exploration Vehicle (CEV)
    - Crew Launch Vehicle (CLV)
    - Robotic Lunar Exploration Program
    - Lunar Sortie Missions
  - Defer development of long-term technologies for lunar base and Mars exploration until needed
- Technology Development Program includes past elements
  - ESR&T program
  - Life support and environmental control from HSR&T program

Energy Storage Project Background

- Energy Storage Project Plan encompasses two tasks
  - Task 4E – Lithium-Ion Batteries
  - Task 4B – Fuel Cells for Surface Systems
- Numerous existing program efforts folded into a single focused Exploration effort
  - Batteries
    - NASA Aerospace Flight Battery Program (led by GRC)
    - Advanced Electrochemical Energy Storage in Power, Propulsion, and Chemical Systems (led by JPL)
    - Advanced Batteries for Space (led by T/J Technologies, Inc.)
  - Fuel Cells
    - PEMFC Power Plant Development (led by GRC in partnership with Teledyne Energy Systems, Inc.)
    - High Energy Density Regenerative Fuel Cell (RFC) Development (led by Lockheed Martin Space Corporation)

Exploration Technology Development Program

ENERGY STORAGE PROJECT

Fuel Cells For Surface Systems and Space Rated Lithium-Ion Batteries

Brief Description

- ESAS architecture requires advanced Fuel Cell and Battery Technologies to meet power requirements.
- Proton Exchange Membrane (PEM) fuel cell technology offers major advances over existing alkaline fuel cell technology including: enhanced safety, longer life, lower mass, higher peak-to-nominal power capability, compatibility with propulsion grade reactants.

Participating Centers: GRC (Lead), JSC, JPL, KSC

- Lithium-ion battery technology offers higher specific energy, lower mass & volume.
- Includes NASA LEO Verification Battery Life-Cycle Test Program.

Participating Centers: GRC (Lead), JPL, JSC, GSFC, MSFC

Key Milestones

Milestone	Year
Achieve TRL-6* with Primary Active PEM Fuel Cell System (*does not meet projected flight requirements)	2006
Complete Upgraded Passive PEM Fuel Cell Breadboard (TRL-5) Performance Test	2007
Achieve 10,000 LEO cycles - SOA Li-ion cell (TRL4)	2006
Qualify 1st human-rated modular battery design (TRL-5)	2008
Deliver modular battery with qualified charge control electronics (TRL-6)	2011
Achieve TRL-6- Primary Passive PEM Fuel Cell System	2012

Deliverables

Fuel Cell:

- Develop PEM Fuel Cell Technology in the 1 to 10kW power range including generic elements with applications below 1 kW and above 10kW.
- Develop passive components to reduce system complexity, system mass and increase efficiency of PEM fuel cell.

Applicable to CEV, Lunar Surface- LSAM, Rovers, Habitat, RLEP

Lithium-Ion Battery:

- Develop/demonstrate advanced technologies for a human-rated lithium-ion battery with improved life and broad temperature operating range.

Applicable to CEV,CLV, LSAM, & lunar surface systems.

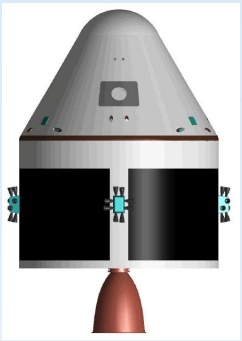
Budget

Energy Storage Project Budget (Direct Costs $K)

	FY06*	FY07	FY08	FY09	FY10	FY11
Fuel Cell	5000*	1932	1673	1673	7796	9836
Li-Ion Battery	3500*	3382	2927	2927	3031	3935
Total	8500*	5314	4600	4600	10827	13771

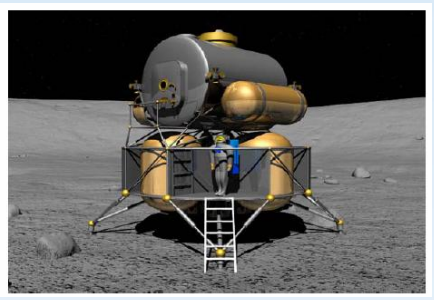
* Full Cost Dollars

ESMD ENERGY STORAGE APPLICATIONS



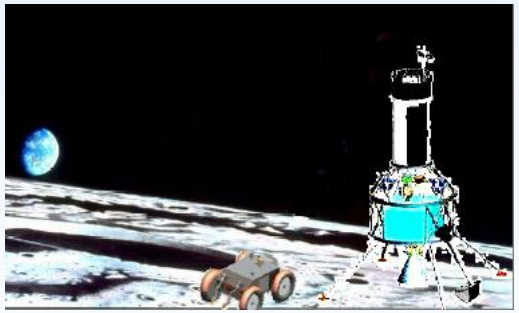
CEV (CM/SM)
5-10 kWh Li-Ion battery

CLV (125 ton)
Li-Ion Batteries

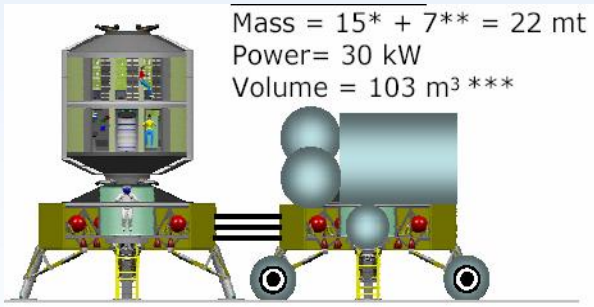


LSAM
13.5 kWh Li-Ion battery

EVA Suit
Li-ion/Fuel cell
200 W for 8 h



Rovers/Landers
Li-Ion Batteries – 1-10 kWh
Fuel cells 10 kWh



Lunar Habitat
Surface Power Systems
30 kW Li-Ion /Fuel cell

Constellation Elements that will Require Energy Storage

- CEV
  - Service Module, Command Module
    - Basic requirements- high specific energy and energy density
- CLV
  - Thrust Vector Control (TVC), Upper Stage (US)
    - TVC basic requirements - high voltage system, high specific power, pulsed profile
    - US basic requirements - high specific energy and energy density
- LSAM
  - LEO phase, LLO phase, Ascent phase (from Lunar Surface)
  - Electrochemical energy storage is one approach being traded-off to meet these needs. Other power generation options are also under consideration.
- EVA
  - Space suit power system
    - Basic requirements – high energy, wide operating temperature, rapid recharge
- General observations
  - Mass reduction is critical to meet launch weight targets
  - Cycle life requirements are not challenging for SOA Lithium-ion systems
  - Many of the missions will be manned. Human-rated systems will be required if batteries are housed in or near crew compartment– stricter qualification process, safety issues with lithium-ion must be adequately addressed
  - Currently, the thermal environment the energy storage system must operate under is poorly defined in many cases– may affect battery capacity requirements, thermal control of battery

Lithium-Ion Battery Objectives and Targets

Object Description	Measurable Technology Metric	State-of-the-Art (SOA)	Performance Goal (Full Success Criterion)	Performance Goal (Min. Success Criterion)	Validation Method
Develop advanced components for Space-rated Li-ion cells	•Cathode specific capacity •Operational temp. °C •Safety	•150 mAh/g •-20°C to +40°C • Includes aux. controls - PTC shutdown separator	•250 mAh/g @25°C •-60°C to +60°C •Tolerant to mild abuse overcharge and over-temperature	•180 mAh/g @25°C •-40°C to +40°C •Non-flammable electrolyte	Laboratory screening of components to demonstrate performance in coin cells
Develop Space-rated advanced Li-ion cell	•Specific Energy •Energy Density •Operating temp. •Safe •Calendar life •Cycle life	•130 Wh/kg •320 Wh/l • -20°C to +40°C • aux. controls • >3 years • 1500 cycles	TRL6 •180 Wh/kg •400 Wh/l •-60°C to +60°C •Non-explosive •5 years •2000 cycles	TRL6 •140 Wh/kg •350 Wh/l •-40°C to +40°C •Reduced abuse hazards •5 years •1500 cycles	Demonstrate performance in prototype aerospace cells
Develop and Qualify Space-rated Li-Ion batteries	•Specific Energy •Energy Density •Operating temp. •Human-rated •High power •Calendar life •Cycle life	•90 Wh/kg •250 Wh/l •-20°C to +40°C •<3 years •1500 cycles	TRL6 •140 Wh/kg •300 Wh/l •-60°C to +60°C •Non-explosive •500 W/kg •5 years •1500 cycles	TRL6 •120 Wh/kg •280 Wh/l •-40°C to +40°C • abuse tolerant •400 W/kg •5 years •1500 cycles	Demonstrate performance in prototype EM battery modules
Develop charge control methods for Space-rated Li-Ion batteries	•Fast Recharge rate •Safe •Reliable	•Benign slow charge rates C/4 •Relies on critical cell matching •TBD	TRL4 •C rate at +25°C •C rate at 0°C •C/2 rate at -20°C •No Li plating •overcharge / over-discharge tolerant •Over-discharge tolerance	TRL4 •C rate at +25°C •C/2 rate at 0°C •C/5 rate at -20°C •No Li plating •overcharge/over-discharge tolerant •Cell balance	Demonstrate stable voltage and capacity performance together with prototype cells and batteries

Typical Lithium-ion Cell and Battery Designs

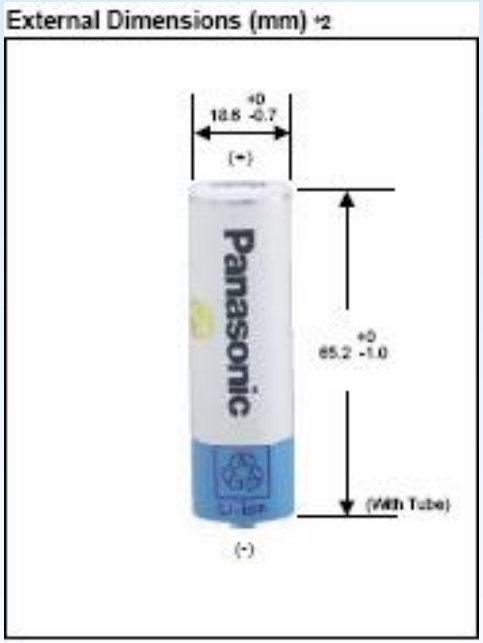
Saft Cylindrical
Lithium-Ion Cell

Saft VL10E
Battery 2P8S

Lithion Prismatic Lithium-Ion Cell

8 Cell, 28 Volt Battery

Alternate Battery Module Concepts



18650 Lithium-ion Cell
Commercial Cell Design

Various Series/Parallel 18650 Cell Configurations Provide Flexible Voltage and Ampere-hour Capacity

Lithium-Ion Cell Material Development Activities

- Electrolytes
  - Synthesize new liquid electrolytes to enable low-temperature operation
  - Develop polymer-based electrolytes to provide higher specific energy
    - Lithium-ion Conducting Polyelectrolytes
    - Plasticized/ionic liquids
- Cathode
  - Improve specific capacity
    - Lithiated MnNiCo oxide chemistries
    - Layered metal oxide chemistries
    - Lithium iron phosphate
- Anode
  - Carbon:Carbon composite substrate
  - Silicon composite
- Shutdown Separator
  - Customize pore size/flow temperature to provide safety feature to avoid thermal runaway condition

Lithium-Ion Cell Activities

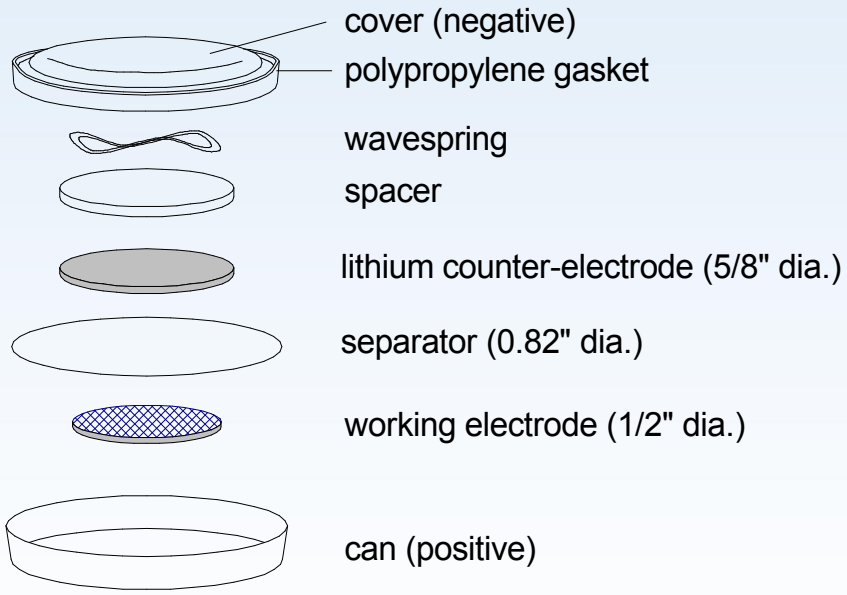
- Screen components through a design-of-experiments approach
  - Assess impacts and interactions in coin cells
  - Provide statistical basis for preferred cell features
- Insert new component materials into cell product line
  - Specify multiple lithium-ion cell design to vendors (Generation 1, 2, 3)
  - Fabricate small production lot to evaluate performance
    - Acceptance
    - Characterization
    - Abuse
    - Life cycle
  - Conduct Destructive Physical Analysis on cells to investigate failure modes
    - Conduct autopsy on new cells and at various stages of cycled cells
    - Provide recommendations for cell design improvements for next cell generation
    - Conduct safety/abuse testing to assist in human-rated certification process
- Baseline preferred cell design for near-term Exploration missions

Lithium-Ion Battery Module Activities

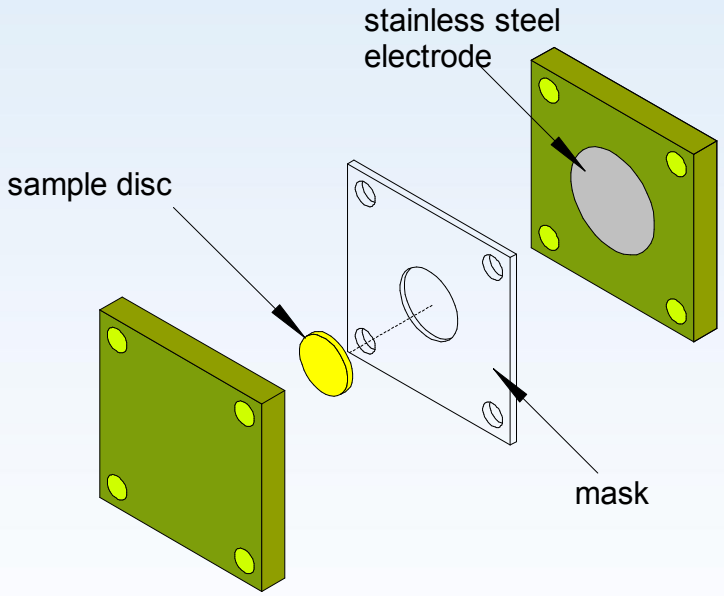
- Conduct trade studies to determine optimum battery module for multiple Exploration Missions
  - Drivers include voltage, ampere-hour capacity, cycle life, thermal considerations, structural loads, and commonality
- Develop common battery module design that meets performance requirements
  - Module can accept lithium-ion cells from multiple vendors
  - Power, thermal, and data interfaces are controlled
- Fabricate module with Generation 1 cells
  - Integrate charge control circuitry and software with the module
  - Conduct acceptance level testing
  - Perform environmental qualification testing to attain TRL 5
  - Conduct mission profile testing to quantify performance degradation
    - Low-Earth-orbit (LEO) cycling
    - Low-lunar-orbit (LLO) cycling
    - Cruise operations where the module is in a charged mode only

Component Screening Hardware

Coin cell

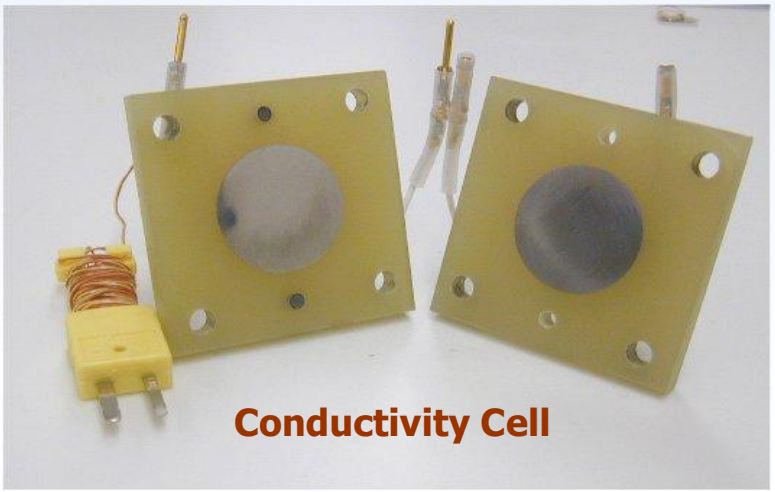


Conductivity Cell



Typical Laboratory Scale Hardware

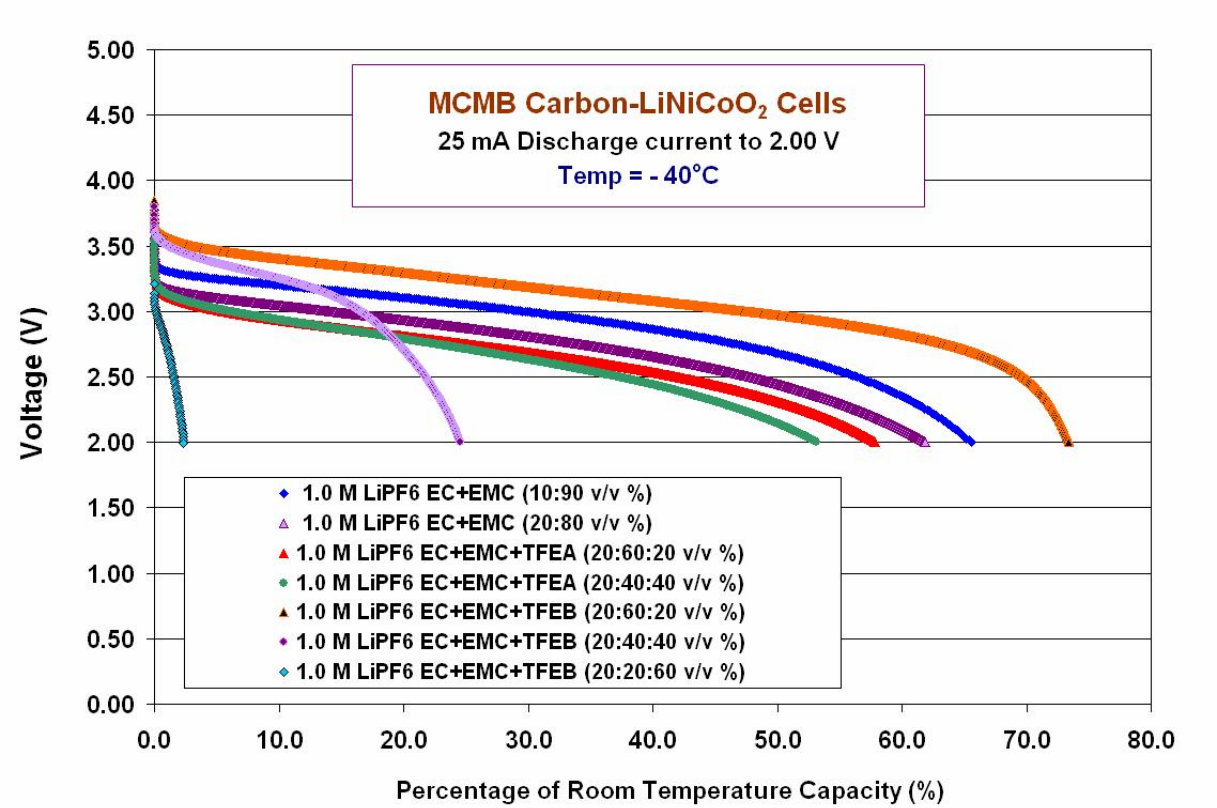
Developed multiple cell configurations for component evaluation



Milestone on Low Temperature (-40°C) Electrolyte

Evaluation of Fluoroester-Based Low Temperature Electrolytes

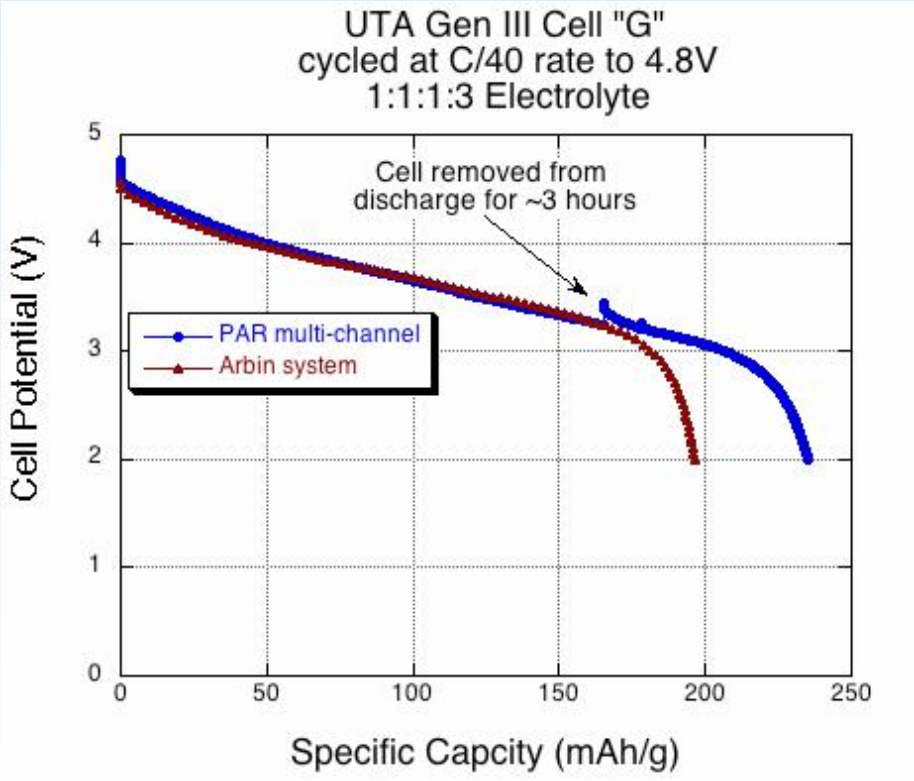
Discharge Characterization at Various Temperatures



- **The cell containing the 1.0 M LiPF6 in EC+EMC+TFEB (20:60:20 v/v %) delivers superior performance at low temperature compared to previously evaluated electrolytes.**

Milestone on 250 mAh/g Cathode Confirmation Tests at JPL

- Initially observed lower capacity that was attributed to a calibration error from the (Arbin) cycler. Once corrected, high capacities of ~ 230 mAh/g were obtained.
- The kinetics of this materials are still poor, especially at low temperatures.
- Improved performance is expected by incorporating a series of coatings on high specific capacity cathode materials to yield better discharge rate performance.



Test and Demonstration Task Breakdown

- Purpose
  - To evaluate the performance of cell and battery products developed through other tasks in this program
  - To assess and validate the performance of state-of-the-art lithium-based secondary cells and batteries to meet a wide variety of Constellation missions

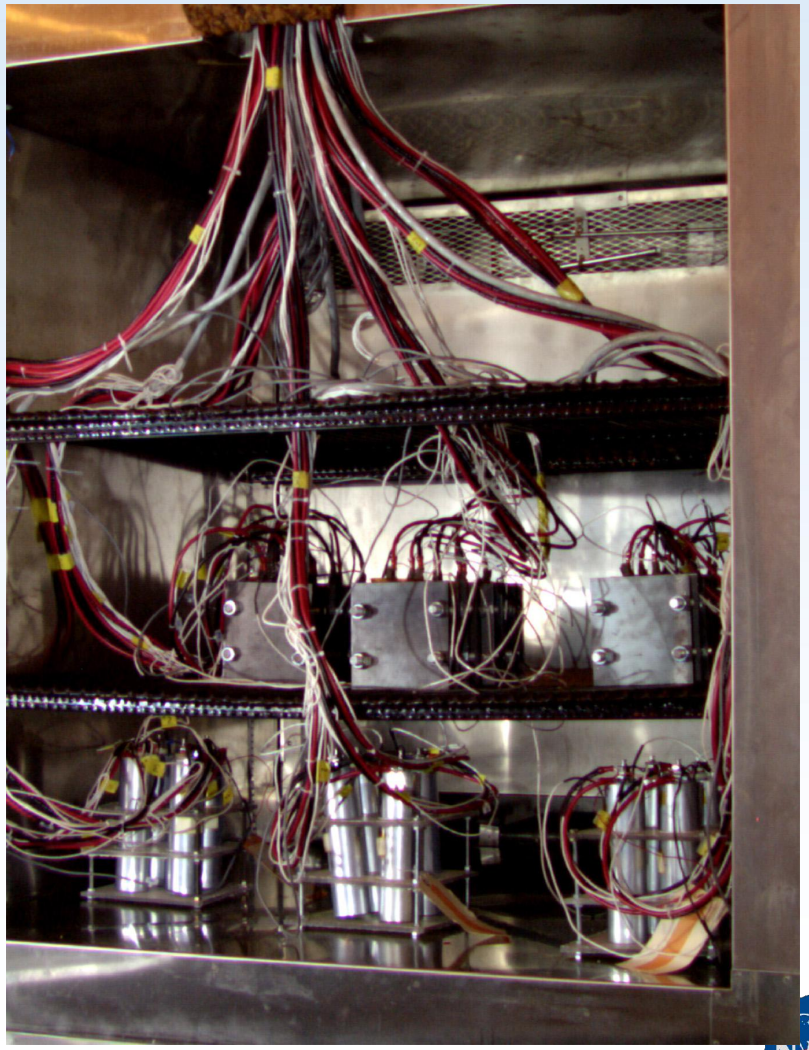
NASA Lithium-Ion Cell Verification Test Program

- LEO life test to generate data for model
- Statistical Design-of-Experiments (DOE) to predict life of cells operating in LEO regimes
- Variables: Depth-of Discharge (DOD)
  Temperature (^{0}C)
  End of Charge Voltage (EOCV)
- 40 cells each from multiple vendors
- Testing being conducted at Naval Facility in Crane, IN
- Program structure allows for cells from additional vendors to enter program when funding allows

Lithium-Ion LEO Verification Test Program

Test Articles

- 40 Lithion (30 Ah) cells
  - INCP 95/28/154
  - Delivered 4/02
- 40 Saft (40 Ah) cells
  - G4 chemistry space cells (HE54245)
  - Delivered 4/02
- 40 MSA (50 Ah) cells
  - 50G01
  - Delivered 10/05
- 20 4s-2p modules of Sony HC 18650 cells from ABSL
  - 4S-2P-SSTB
  - Delivered 7/05



Lithium-Ion LEO Verification Test Program

Testing

- Acceptance Testing
- Characterization Testing
- Actual Capacity Determination
- Self-Discharge Rate
- Capacity at Specific LEO Test Conditions
- Life Cycling at LEO Test Conditions

  Cell test conditions for LEO test are based on average actual discharge capacity between 4.1 V to 3.0 V measured at C/2 and 20°C

LEO Test Matrix

Temp(°C)	Voltage/cell	DoD
30	4.05	20
30	3.85	20
10	3.85	20
30	3.95	30
20	3.95	20
10	3.85	40[1]/35[2]
20	3.85	30
30	3.85	40[1]/35[2]
20	4.05	40[1]/35[2]
10	4.05	30

1 - Lithion, MSA, ABSL

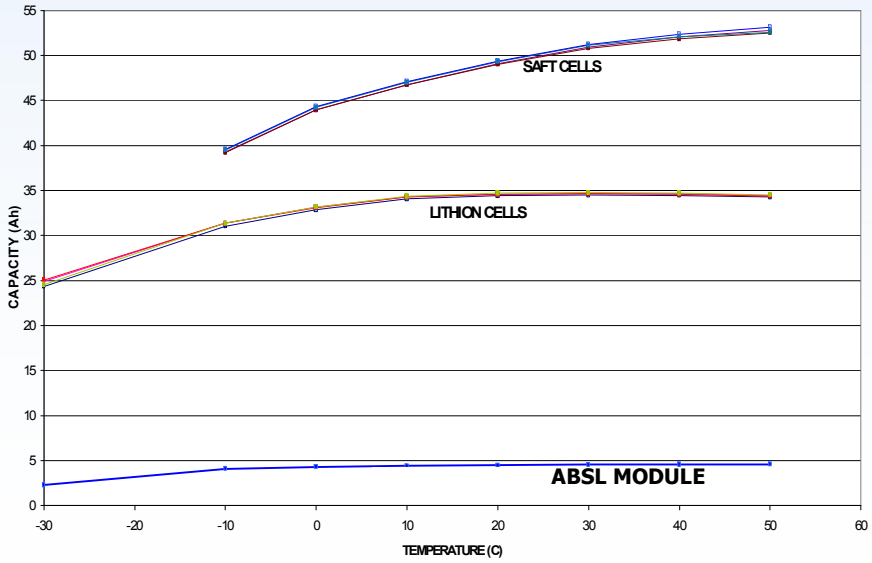
2 - Saft

Lithium-Ion LEO Verification Test Program

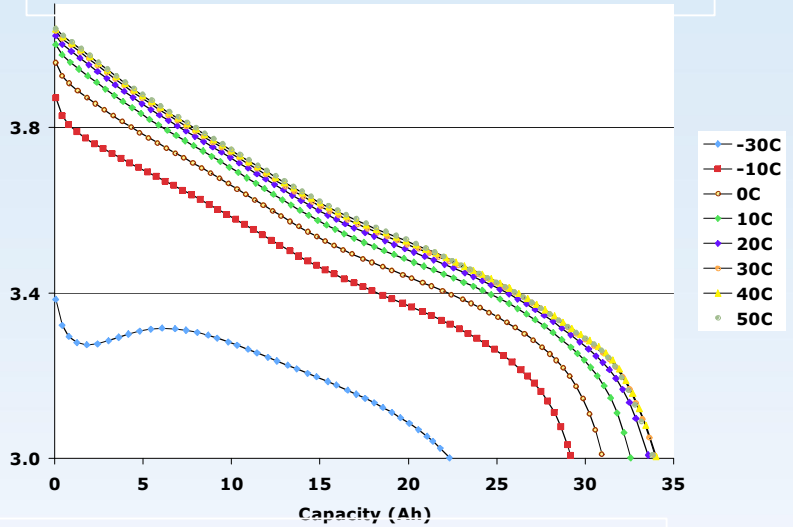
Characterization Test Results

- Capacity measured at temperatures:
  -30°C, -10°C, 0°C, 10°C, 20°C, 30°C, 40°C, 50°C
- Saft cells would not cycle at -30°C
- Two ABSL modules were connected together to form 4S-4P modules

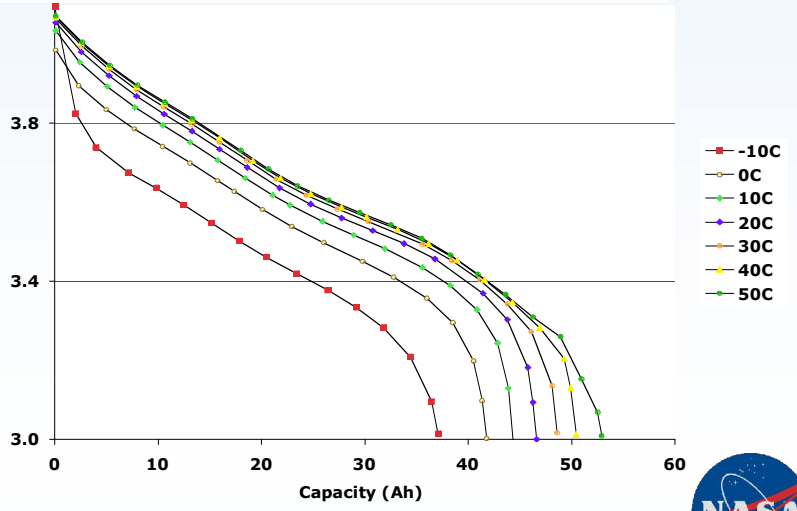
Capacity vs Temperature

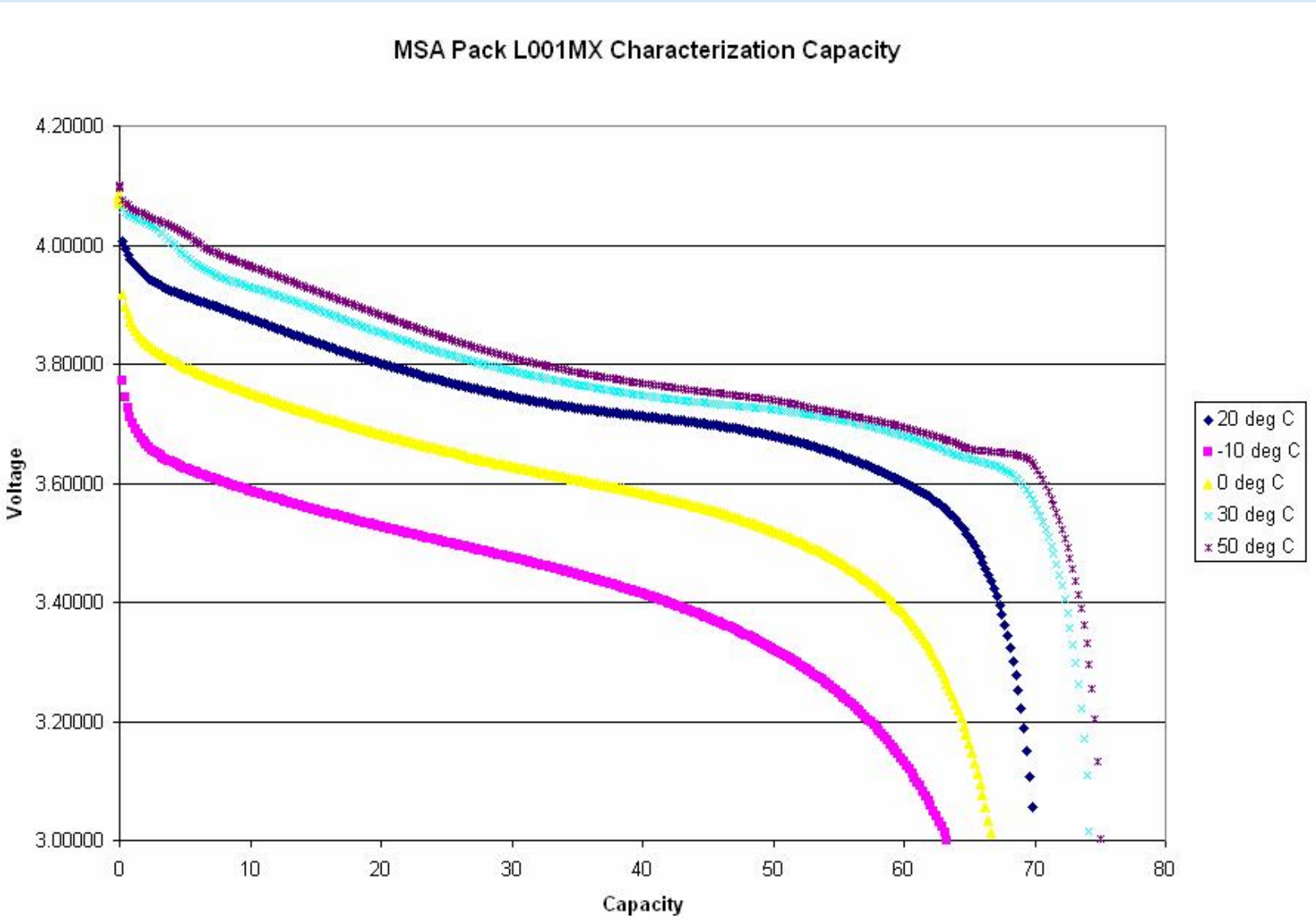


Lithion



Saft





- No data for -30°C

Cell Assessment and Validation

- Battery Level Performance evaluation
  - 2001 Mars Surveyor Program Lander Battery Life Test
    - Heritage LEO life test initiated in 2003
    - 40% DOD , 0 °C, 32 V EOCV
    - Has achieved 12000+ cycles to date

Cell Assessment and Validation

- Cell Level performance evaluations
  - Evaluation of cells to meet a wide variety of Exploration mission requirements
  - Standard test plan for baseline cell performance evaluation
    - Includes stabilization, actual capacity determination, capacity and internal resistance performance, cycle life testing, discharge rate capability, charge rate capability, and mission profile testing
    - Adjustments to standard procedures can be made for cells with special capabilities
    - Plan can be modified to perform fewer test when only a limited number of cells are available (due to budget or other constraints)
  - Test plan calls for mission profile testing
    - Will vary by mission, mission requirements are not fully defined, preliminary power/energy storage requirements are being worked in the various Constellation studies our group supports
  - Data on baseline performance characteristics can be shared across missions

Battery Module Development

- Identify a common battery module that can be used across multiple mission platforms
- Based upon the results of the overall trade studies that address bus voltage, energy, and power capabilities specify a battery design concept to ensure the best form, fit, and functional match with Exploration energy storage requirements
  - Identify minimum building block size – cell capacity
  - Qualification of high energy density and/or high power cell building blocks
  - Qualification of modules consisting of qualified Gen-1 cells
  - Include results of charge control studies and development of developmental electronics to control cell charging at the module level
  - Modules can be scaled up into batteries and ORUs to meet energy storage requirements for individual missions
  - Plug and Play capability to accommodate series and parallel configuration
- Design, develop, and qualify the module/battery at TRL6

Battery Module Qualification

- Planned testing at GRC includes:
  - –Functional performance
  - –Acceptance level
  - –Acoustic
  - –Random vibration
  - –Shock
  - –Thermal vacuum
  - –Post Functional performance

- Upon successful qualification testing to TRL6, the battery module will be placed on life test in FY08 to provide long term performance at the anticipated key mission design point.

Task 4E Space-Rated Lithium-Ion Battery

Concluding Remarks

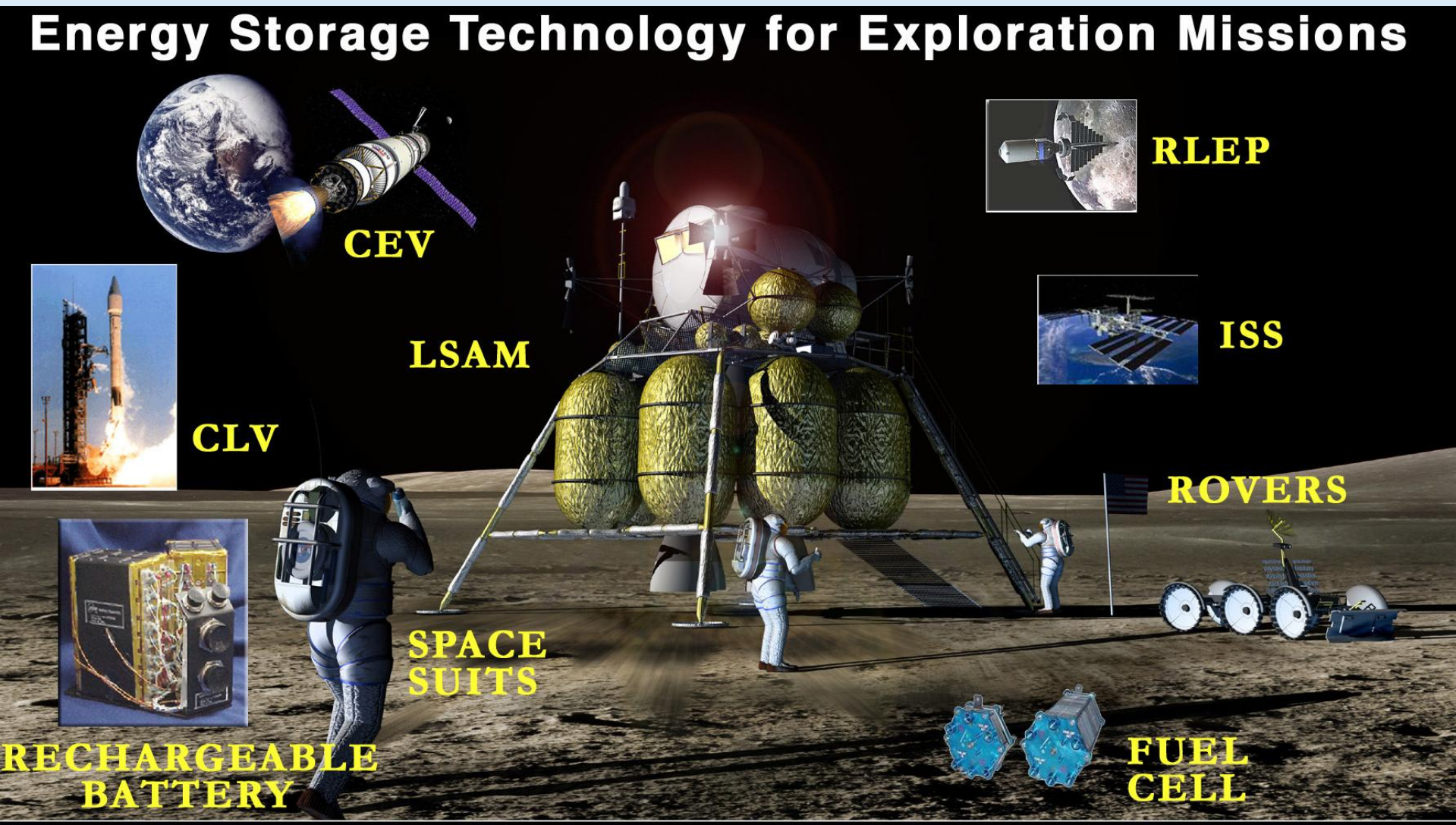
- Verification for Exploration Applications
  - –Cycle life and calendar life
  - –Charge and Discharge Rate capability
  - –Performance over a wide temperature range
  - –Safety/abuse tolerance for Human-rated battery technology
  - –Cell/Battery module level performance
- Lithium-ion is a viable energy storage technology to meet NASA's future Exploration Mission Requirements

Back-Up Milestone Charts

Exploration Architecture Elements and Energy Storage Needs

ESAS Architectural elements	Missions/ Applications	Energy System Sizing	Li-Ion Battery Technology Development Drivers	PEM Fuel Cell Technology Development Drivers
Crew Exploration Vehicle (CEV) 2009 Test Flight 2011 Crewed Flight	Command Module (CM) Service Module (SM)	• 5-10 KWh • 4.5 kW Ave 3X 28 V bus	• Human-rated (Safety) • High energy density • Long life, high power • High temp. resilience	• Primary Fuel Cell • High Voltage Performance • Long Life • System Simplicity • Low Mass & Volume
	Crew Launch Vehicle (CLV)		• Human-rated (Safety) • High energy density • Long shelf life, high power • High temp. resilience	
Lunar Surface Access Module (LSAM) • 2010 Begin Effort • 2012-2013 Tech • Insertion • 2017 First Launch	Ascent Stage	• 13.5 kWh • 3 x 28 V bus	• Human-rated (Safety) • High energy density • Long life, high power • High temp. resilience	• Primary Fuel Cell • High Voltage Performance • Long Life • System Simplicity • Low Mass & Volume
Sorties RLEP2- 2011- 2012	EVA	• 0.1- 1 kW	• Human-rated (Safety) • High energy density • Long shelf and calendar life, high power • Low and high temp performance	• Regenerative Fuel Cell • High Electrical Efficiency • High Energy Density • Long Life • System Simplicity • Low Mass & Volume
	Un-pressurized Rovers/landers	• 1 kW	• Low and high temp performance • High energy density • Long life, high power	• Primary Fuel Cell • High Voltage Performance • Long Life • System Simplicity • Low Mass & Volume
Outpost Missions 2020- 2022	Un-pressurized Rovers/landers	• 1 kW		
	Pressurized Rovers/landers	• 1-5 kW	• Human-rated (Safety) • High energy density • Long cycle life, high power • Low and high temp performance	• Primary Fuel Cell • High Voltage Performance • Long Life • System Simplicity • Low Mass & Volume
	Fuel cell/battery hybrid power Station	• 10-100 kW	• Human-rated (Safety) • High energy density • Long cycle life, high power	• Regenerative Fuel Cell/ • High Electrical Efficiency • Long Life • System Simplicity • Low Mass & Volume

Energy Storage Technology for Exploration Missions



NASA Glenn Research Center

Kennedy Space Center
Jet Propulsion Laboratory

Johnson Space Center
Marshall Space Flight Center

Table 2-1 Energy Storage Project Milestones and Deliverables FY 2006

WBS	Tasks	Milestones	Deliverables	Date
1.0	**Management**	• Kickoff • Confirmation Review • Complete detailed WBS task plan schedule • Complete detailed Planning FY07	• Project Plan signed/completed • Deliver final WBS, Task Plan, schedule • Initial Risk Assessment • Deliver Updated WBS, Task Plan, Schedule	• 2Q06 • 2Q06 • 2Q06 • 3Q06 • 4Q06
2.1	**Exploration Systems Requirements**	• Complete Exploration Energy Storage Requirements Document	• Requirements Document	• 3Q06
2.2	**Trade Studies**	• Complete Gap Analysis • Complete trades studies	• Trade Study Reports	• 3Q06 • 4Q06
3.1	**Battery Cell Development**	• Demonstrate cathode with 250 mAh/g (Gen-1) • Demonstrate liquid electrolyte for -40 to + 50°C operation with cathode (Gen-1) • Define polyelectrolyte conductivity limits • Complete fabrication of test cells with best GRC polymer electrolyte (T/J) • Complete scale up batch of T/J lithium iron phosphate (LFP) cathode powder (T/J) • Complete carbon-carbon anode cell development (negative voltage capability) for improved safety • Complete pressure measurements on different Li-ion cell configurations	• Gen-1 Cathode-250 mAh/g • Gen-1 Electrolyte for -40 to + 50°C operation • Report on conductivity test results and definition of development effort required • Pouch cells for evaluation • Report on carbon-carbon anode performance/safety • Report on cell pressure measurements on different Li-ion cell configurations	• 3Q06 • 3Q06 • 4Q06 • 4Q06 • 4Q06 • 4Q06 • 4Q06
3.2	**Battery Development**	• Initiate study on alternate charge methodologies		• 4Q06
3.3	**Test and Demonstration**	• Initiate Li-ion cell testing to assess effects of current charging methodologies • Achieve 10,000 LEO cycles/SAFT and Lithion cells (NASA Li-ion Test Verification Program) • Complete first year performance and safety assessments of SOA cells for Exploration Missions • Complete evaluation of cells with variable temperature shutdown separator incorporated • Complete safety testing and tear-down analysis of SOA commercial-off-the-shelf (COTS) and aerospace Li-ion cells	• Demonstration of performance, flow of data into performance model • Reports on the performance and safety of cells for Exploration Missions • Report on shutdown separator results • Report on SOA safety testing on aerospace Li-ion cells	• 2Q06 • 4Q06 • 4Q06 • 4Q06 • 4Q06
3.4	**Multi-Mission Support**	• Publish Battery Workshop Proceedings • Complete build of Li-ion battery cell testbed for real-time observer (model Li-ion cell performance)	• Battery Workshop Proceedings	• 3Q06 • 4Q06

Table 2-4 Energy Storage Project Milestones and Deliverables FY 2009

WBS	Tasks	Milestones	Deliverables	Date
1.0	**Management**	• Complete updated Project Plan	• Deliver updated Project Plan	• 4Q09
2.0	**Energy Storage Systems**	• Complete Requirements Update • Complete Gap Analysis		• 3Q09 • 3Q09
3.1	**Battery Cell Development**	• Complete performance testing of Gen-2 Li-ion cells for Exploration Missions • Complete Destructive Physical Analysis (DPA) of Gen-2 Li-ion cells containing component enhancements	• Gen-2 Li-ion cells and report on the performance and safety of Gen-2 Li-ion cells • Report describing failure modes of Gen-2 Li-ion cells	• 4Q09 • 4Q09
3.2	**Battery Development**	• Final assessment of charge methodologies • Incorporate results of pressure studies into design for high voltage and/or high capacity batteries for lander/rover applications, using cells with variable temperature shutdown separator incorporated	• Charge methodologies report • 20 kWh, 70 to 85 V battery design	• 4Q09 • 4Q09 • 4Q09
3.3	**Test and Demonstration**	• Complete fourth year performance and safety assessment of Li-ion cells for Exploration Missions • Test and validate battery module engineering model	• Reports on the performance and safety of SOA cells for Exploration Missions • Validated battery module engineering model	• 4Q09 • 4Q09
3.4	**Multi-Mission Support**	• Convene NASA Aerospace Battery Workshop • Publish Battery Workshop proceedings	• Battery Workshop Proceedings	• 1Q09 • 3Q09

Table 2-2 Energy Storage Project Milestones and Deliverables FY 2007

WBS	Tasks	Milestones	Deliverables	Date
1.0	**Management**	• Complete detailed FY08 planning	• Deliver updated WBS, Task Plan, schedule	• 4Q07
2.0	**Energy Storage Systems**	• Complete Requirements Update • Complete Gap Analysis		• 3Q07 • 3Q07
3.1	**Battery Cell Development**	• Complete fabrication/qualification of prismatic 7 Ah cells with LFP cathode (T/J) • Complete evaluation of GRC polymer (T/J) • Quantify technical feasibility of gel-polymer/solid polymer electrolytes to meet Exploration goals • Approach to polyelectrolyte interfacial impedance practical technical barrier issue defined • Demonstrate cathode with enhanced thermal stability • Synthesize non-flammable Electrolyte (Gen-1) • Fabricate and characterize prototype cells with Gen-1 components • Complete pressure studies on large capacity Li-ion cells • Identify life-limiting mechanisms of SOA Li-ion cells • Destructive Physical Analysis (DPA) of Gen-1 Li-ion cells containing component enhancements	• Twenty prismatic cells delivered • Report on performance and recommendation • Report on technical evaluations of candidate technologies and further definition of polyelectrolyte development task • Report and proposal task plan for polyelectrolyte development task • Gen-1 cathode • Gen-1 Non-flammable electrolyte • Li-ion prototype cells with Gen-1 components • Report on pressure studies for large capacity cells • Report on life-limiting mechanisms • Report on DPA of Gen-1 Li-ion cells	• 1Q07 • 2Q07 • 2Q07 • 3Q07 • 3Q07 • 3Q07 • 4Q07 • 4Q07 • 4Q07 • 4Q07
3.2	**Battery Development**	• Complete preliminary assessment of charge methodologies • Commence battery module design to meet Exploration requirements	• Preliminary Report on charge methodologies	• 1Q07 • 2Q07
3.3	**Test and Demonstration**	• Achieve 5,000 LEO cycles/AEA modules and MSA cells (NASA Li-ion Test Verification Program) • Complete second year performance and safety assessment of Li-ion cells for Exploration Missions • Complete pack-level testing of SOA Li-ion cells for Exploration Missions • Complete testing on charge methodologies	• Flow of data into performance model • Reports on the performance and safety of SOA cells for Exploration Missions • Report on the performance of SOA Li-ion packs for Exploration Missions • Report and recommendations on best practices for charging Li-ion cells	• 3Q07 • 4Q07 • 4Q07 • 4Q07
3.4	**Multi-Mission Support**	• Convene NASA Aerospace Battery Workshop • Publish Battery Workshop proceedings	• Battery Workshop Proceedings	• 1Q07 • 3Q07

Table 2-3 Energy Storage Project Milestones and Deliverables FY 2008

WBS	Tasks	Milestones	Deliverables	Date
1.0	**Management**	• Complete detailed FY09 planning	• Deliver updated WBS, Task Plan, schedule	• 4Q08
2.0	**Energy Storage Systems**	• Complete Requirements Update • Complete Gap Analysis		• 3Q08 • 3Q08
3.1	**Battery Cell Development**	• Demonstrate high energy cathode - 1000 Wh/kg (Gen-2) • Formulate electrolyte for -60 to + 60°C operation • Synthesize non-flammable Electrolyte (Gen-2) • Complete performance assessment of Gen-1 Li-ion cells for Exploration Missions • Complete Safety tests on Gen-1 Li-ion polymer cells	• Gen-2 cathode (1000 Wh/kg) • Electrolyte for -60 to + 60°C operation • Gen-2 Non-flammable electrolyte • Report on the performance and safety of Gen-1 Li-ion cells for Exploration Missions	• 3Q08 • 3Q08 • 3Q08 • 4Q08 • 4Q08
3.2	**Battery Development**	• Complete development/evaluation of charge control electronics for batteries/modules • Complete control software based on preliminary results of Li-ion charging methodologies testing and studies • Complete pressure studies on cell modules • Complete battery module engineering model	• Charge control electronics • Charge control software/program • Report on module performance/safety • Battery module engineering model	• 2Q08 • 3Q08 • 4Q08 • 4Q08
3.3	**Test and Demonstration**	• Complete third year performance and safety assessment of Li-ion cells for Exploration Missions • Commence Qualification test of Battery Module	• Reports on the performance and safety of Li-ion cells for Exploration Missions	• 4Q08 • 4Q08
3.4	**Multi-Mission Support**	• Convene NASA Aerospace Battery Workshop • Publish Battery Workshop proceedings	• Battery Workshop Proceedings	• 1Q08 • 3Q08

Table 2-4 Energy Storage Project Milestones and Deliverables FY 2009

WBS	Tasks	Milestones	Deliverables	Date
1.0	**Management**	• Complete updated Project Plan	• Deliver updated Project Plan	• 4Q09
2.0	**Energy Storage Systems**	• Complete Requirements Update • Complete Gap Analysis		• 3Q09 • 3Q09
3.1	**Battery Cell Development**	• Complete performance testing of Gen-2 Li-ion cells for Exploration Missions • Complete Destructive Physical Analysis (DPA) of Gen-2 Li-ion cells containing component enhancements	• Gen-2 Li-ion cells and report on the performance and safety of Gen-2 Li-ion cells • Report describing failure modes of Gen-2 Li-ion cells	• 4Q09 • 4Q09
3.2	**Battery Development**	• Final assessment of charge methodologies • Incorporate results of pressure studies into design for high voltage and/or high capacity batteries for lander/rover applications, using cells with variable temperature shutdown separator incorporated	• Charge methodologies report • 20 kWh, 70 to 85 V battery design	• 4Q09 • 4Q09 • 4Q09
3.3	**Test and Demonstration**	• Complete fourth year performance and safety assessment of Li-ion cells for Exploration Missions • Test and validate battery module engineering model	• Reports on the performance and safety of SOA cells for Exploration Missions • Validated battery module engineering model	• 4Q09 • 4Q09
3.4	**Multi-Mission Support**	• Convene NASA Aerospace Battery Workshop • Publish Battery Workshop proceedings	• Battery Workshop Proceedings	• 1Q09 • 3Q09